

Chapter 1 Introduction

We propose to search for the rare process $\mu^- N \rightarrow e^- N$ with far greater sensitivity than in any past experiment. Muon to electron conversion does not conserve the additive quantum numbers, L_e and L_μ , associated with the electron and muon and their corresponding neutrinos. Non-conservation of these quantum numbers, and that of the third lepton, L_τ , is commonly referred to as lepton flavor violation (LFV). The observation of this process provides direct evidence for lepton flavor violation and requires new physics, beyond the usual Standard Model and the minimal extension to include massive neutrinos.

The experiment, dubbed MECO for Muon to Electron Conversion, will be conducted in a new μ^- beam-line at the Brookhaven National Laboratory (BNL) Alternating Gradient Synchrotron (AGS), produced using a pulsed proton beam. The proton energy will be ~ 8 GeV for a variety of reasons discussed at length in the proposal. The expected sensitivity, normalized to the rate for the kinematically similar process of muon capture, is one event for a branching fraction of 2×10^{-17} for a data taking period of 30 weeks at full design intensity. Current calculations of the expected background rates indicate that increased running time would result in even better sensitivity.

In this proposal, we review the physics motivation for such a search, discuss the present status and expected results of other experiments with related goals, outline the basic ideas of the experiment, and discuss the status and results of studies of the important experimental issues.

We believe that this experiment has a real chance of making a discovery of profound importance. This physics cannot be addressed at the *high energy frontier*. In many theoretical models there is no particular reason to believe that lepton flavor violation is more likely in the τ lepton sector, and making significant improvements in that sector will be quite difficult. It is very unlikely that lepton flavor violating interactions of high energy hadrons or leptons can be detected directly, and even if this were possible, LFV decays of light particles are a more sensitive probe for any conceivable interaction luminosity at a high energy machine. The largest flux of μ^- 's is produced at existing low energy accelerators and no facility is foreseen at which this experiment could be done better and or on a comparable time scale.

The remainder of the proposal is organized as follows. We first discuss the motivation for and experimental status of muon and electron number violation. We then give an overview of the experimental technique, followed by a discussion of physics backgrounds and signal rates. We discuss the reasons for choosing BNL as the facility at which to do the experiment, and then discuss the new pulsed muon beam and describe in detail the experimental apparatus. We conclude by summarizing the expected results of the experiment, estimating its cost, describing an R & D plan that will allow us to refine the cost estimate and answer the remaining technical questions about the beam and detector, and describing a construction and running schedule that will allow us to obtain physics results by 2010.

1.1 Physics Motivation

Apart from the searches for the Standard Model Higgs particle at LEP II, at Fermilab, and in the future at the LHC, the principal thrust of particle physics research for the foreseeable future is the search for new phenomena, beyond the Standard Model. Precision measurements have verified the predictions of the Standard Model and determined many of its parameters, but the unification of all of the forces,

including gravity, will ultimately require departures from the Model. The Standard Model is incomplete, and the theoretical arguments for extensions to the Model are compelling.

A major search for new phenomena is being mounted at the LHC where, for example, weak scale supersymmetry will be either observed or rejected. The high energy community has invested heavily in the two general purpose detectors, ATLAS and CMS, that will begin taking data after 2007. There is also a chance for discovery at the Tevatron in run II by the scheduled time for turn on of the LHC {Holmes:1999}. In addition to match improved searches for supersymmetry, the study of the dynamics of the production and decay of 1000 top quark events (in run II) may reveal new physics, perhaps even a dynamical mechanism for electroweak symmetry breaking.

In addition to these fundamentally high energy experiments that search for new phenomena at the energy frontier, a host of interesting ‘low energy’ and non-accelerator experiments provide important tests of the Standard Model, and could also reveal departures. Among these are measurements of CP violation in the neutral kaon system, the search for CP violation in B decays, measurements of neutrino mass and mixing in oscillation experiments, precision measurements of electric dipole moments and the $g-2$ of the muon, measurements of flavor changing neutral currents, searches for proton decay, and searches for lepton flavor violating processes— i.e., those that do not conserve L_e , L_μ , or L_τ but do preserve their sum, L , —in the decays of mesons and muons, and in muon to electron conversion.

These low energy experiments also address fundamental questions, most often related to the replication of leptons and quarks in generations: the quark and lepton mass spectra, the mixing of flavors, and the CP violation induced by the mixing. They test interesting predictions based on extensions of the Standard Model, most notably those involving supersymmetry and quark-lepton unification.

Some of the ‘low energy’ experiments are being done at high energy for technical reasons. Thus, copious B production and the advantages of high energy for B-tagging make the CDF and DØ collider experiments competitive in studies of the B system. Not all of the experiments are being pursued with equal vigor. Some have reached limits that are currently difficult to improve upon. Others, such as experiments on B physics and neutrino oscillations, are generally regarded as holding so much potential for discovery that they will be pursued world-wide with enormous energy and resources over the next decade.

The $SU(3)_C \times SU(2)_L \times U(1)_Y$ structure of the Standard Model includes in each generation a color triplet of left-handed u and d states in a weak isodoublet, color triplets of right-handed u_R and d_R quarks, a left-handed weak isodoublet of leptons and a right-handed lepton singlet; fifteen states in all. In the absence of the Yukawa couplings to the Higgs, the three generation states in each of the five configurations cannot be distinguished by the known gauge interactions, and each possesses a $U(3)$ global symmetry corresponding to unitary transformations in generation space. In the Standard Model, the quark masses and mixing introduced through the Yukawa couplings break this symmetry down to $U(1)^4$, the four exact global symmetries of the Standard Model that lead to the empirically well established conserved quantum numbers: B , L_e , L_μ , and L_τ . These symmetries, together with the local gauge symmetries, $SU(3)_C$ and $U(1)_{EM}$, are the exact internal symmetries of the Standard Model.

Lepton flavor is conserved at the charged W vertex, unlike quark flavor, because the neutrinos in the theory are assumed massless. The lepton and neutrino mass matrices can be simultaneously diagonalized (trivially). Many of the questions of particle physics come down to understanding what symmetry replaces this very large $U(3)^5$ global invariance in the inevitable extension of the Standard Model and, ultimately, in nature {Hall:1996}. Which of the horizontal symmetries, those mixing generations,

remain and which of these are gauged? The Standard Model is silent on the replication of generations and on the relationship between quarks and leptons within a generation. It is silent too on the mass spectrum of the fermions and on the size of the flavor mixing parameters. Not all of the answers to these questions will come from experiments at the high energy frontier. The limit on the proton lifetime, which rules out the simplest grand unified extensions, provides input, as do studies of CP violation, directly related to generation mixing, and the observation of neutrino oscillations, implying both non-zero neutrino mass and lepton flavor violation. Limits on flavor changing neutral currents strongly constrain most extensions of the Standard Model, as do limits from the lepton flavor violating processes $\mu \rightarrow e + \gamma$ and muon to electron conversion. Substantial improvements in these measurements could lead to a breakthrough or to further restrictions on theoretical models.

In the Super-Kamiokande neutrino experiment {Fukuda:1998.1} {Fukuda:1998.2} {Fukuda:1998.3} {Fukuda:1999}, strong evidence for a flavor symmetry breaking transition, most likely $\nu_\mu \rightarrow \nu_\tau$ has been observed. The inescapable conclusion is that neutrinos have non-zero mass and mix. A small, but significant, extension of the Standard Model can be made to accommodate this result. While this minimal extension does not conserve lepton flavor, the experimental consequences away from oscillation experiments appear to be small. For example, the process $\tau \rightarrow \mu + \gamma$ proceeds at a rate $\sim (\delta m_\nu^2 / M_W^2)^2$, too small to be observed. In extensions of the Standard Model, including supersymmetric theories that unify quarks and leptons, the analogous processes $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- N \rightarrow e^- N$ can occur at small but observable rates. The distinguishing feature of these super-unified models is that the slepton (supersymmetric partners of the leptons) masses of different generations are different, the degeneracy being split by radiative corrections induced by the large top Yukawa coupling. No longer a multiple of the unit matrix, the slepton and lepton matrices cannot then be simultaneously diagonalized, and the mismatch between the rotations will result in lepton flavor and, in general, CP violation. For example, the lepton- slepton coupling to the neutralino will change lepton flavor. The lepton mixing angles in these models are related to the quark mixing angles. The calculated rates for $\mu \rightarrow e + \gamma$ and muon to electron conversion are still model dependent– they vary with $\tan \beta$, the ratio of the vacuum expectation values of the two Higgs doublets, the masses of the scalar leptons, and other parameters as well – and are generally 2-3 orders of magnitude below the current experimental limits {Barbieri:1994} {Barbieri:1995}. For muon to electron conversion, the ratio

$$R_{\mu e} \equiv \frac{\mu^- + (Z, A) \rightarrow e^- + (Z, A)}{\mu^- + (Z, A) \rightarrow \nu + (Z-1, A)} \quad (1.1)$$

falls in the range 10^{-14} to 10^{-17} over the entire parameter space (see Figure 1.1).

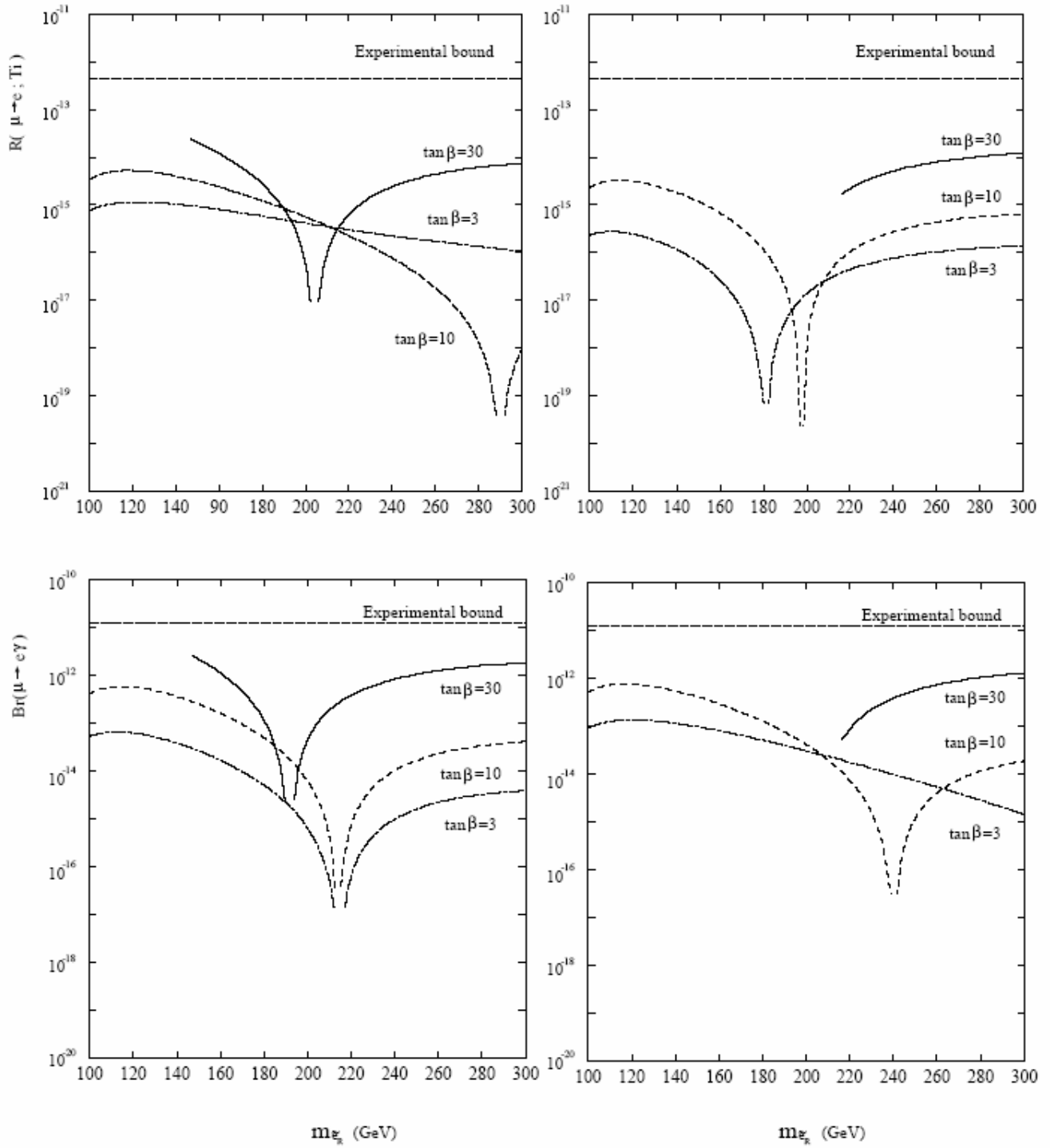


Figure 1.1 Expected rates for $\mu^- N \rightarrow e^- N$ and $\mu^+ \rightarrow e^+ \gamma$ in a minimal supersymmetric SU(5) model {Hisano:1997} for different values of the ratio of the vacuum expectation values of the Higgs particles, $\tan(\beta)$, and the slepton mass. The plots shown are for the parameter $\mu > 0$ (left) and $\mu < 0$ (right). The experimental limits have been updated from the reference to account for recently reported results.

As just described, these models also provide a new source of CP violation, induced by the phase in the lepton mixing matrix. In SO(10) an electric dipole moment of the electron is predicted, whose

magnitude is related directly to the amplitude for the $\mu \rightarrow e$ transition with the initial state muon replaced by an electron.

$$d_e = 1.3 \times 10^{-21} \sqrt{B(\mu^+ \rightarrow e^+ \gamma)} \sin \phi \text{ [e} \cdot \text{cm]} \cong 18.0 \times 10^{-21} \sqrt{R_{\mu e}} \sin \phi \text{ [e} \cdot \text{cm]}$$

where the CP violating phase ϕ , analogous to the phase in the CKM matrix, need not be small {Barbieri:1995} {Dimopoulos:1994}. An experiment at $R_{\mu e} \sim 10^{-17}$ would limit the contribution to the electric dipole moment of the electron from this source to $d_e < 6 \times 10^{-29} \text{ e} \cdot \text{cm}$, one order of magnitude below the current limit {Regan:2002}.

An experiment with this sensitivity would provide a significant test of supersymmetric quark-lepton unification. It would probe many other models as well: those with induced non-diagonal $Z\mu e$ or $H\mu e$ couplings, horizontal gauge bosons, or heavy neutrino mixing. Such an enormously sensitive experiment, improving upon the most recent experiments at the PSI and TRIUMF by three or more orders of magnitude, requires an entirely new and significantly scaled up approach to the measurement. In Section 2 an overview of just how this will be accomplished in the proposed experiment is presented. Details of the experimental design are provided in the remaining Sections.

Table 1.1 Experiments on lepton flavor violation: the current experimental limits, the change in generation number in the model of Cahn and Harari, the effective mass measured and the inferred limits on the mass (updated from the reference for new experimental results).

Process	Limit	ΔG {Cahn:1980}	Measured	Mass limit [TeV]
$K_L^0 \rightarrow \mu^\pm e^\mp$ {Ambrose2:1998} {Arisaka:1993}{Akagi:1991}	4.7×10^{-12}	0, 2	$m_H \frac{\left(\frac{g_W}{g_H}\right)}{\cos \beta_{LU}}$	150
$K_L^0 \rightarrow \pi^0 \mu^\pm e^\mp$ {Krolak:1994}	3.2×10^{-10}	0, 2	$m_H \frac{\left(\frac{g_W}{g_H}\right)}{\cos \beta_{LU}}$	37
$K^+ \rightarrow \pi^+ \mu^+ e^-$ {Lee:1990}	2.1×10^{-10}	0	$m_H \frac{\left(\frac{g_W}{g_H}\right)}{\cos \beta_{LU}}$	21
$\mu^+ \rightarrow e^+ e^+ e^-$ {Bellgardt:1988}	1.0×10^{-12}	1	$\frac{\Delta \left(\frac{g_W}{g_H}\right)}{\sqrt{\cos \beta_{LL} \sin \beta_{LL}}}$	80
$\mu^+ \rightarrow e^+ \gamma$ {Brooks:1999}	1.2×10^{-11}	1	$\frac{\Delta \left(\frac{g_W}{g_H}\right)}{\sqrt{\cos \beta_{LL} \sin \beta_{LL}}}$	21
$\mu^- N \rightarrow e^- N$ {Riepenhausen:1997}	7.8×10^{-13}	1	$\frac{m_H \left(\frac{g_W}{g_H}\right)}{\sqrt{\sin \beta_{LQ}}}$	340

1.2 Current Limits on Lepton Flavor Violation

Limits on lepton flavor violation have been lowered by recent experiments searching for rare decays of kaons and muons. The limits obtained from these experiments are listed in Table 1.1. They are compared in columns 3-5 using the toy model of Cahn and Harari {Cahn:1980}, in which a horizontal gauge symmetry $SU(2)_H$ is mediated by three neutral gauge bosons that are in general non-degenerate in mass and of mass $\sim m_H$ and mass difference $\sim \Delta$. In this two generation model, the *generation number* G is an isospin, $-1/2$ and $+1/2$ for the first and second generations of charged and neutral fermions (leptons and quarks), respectively. Generation number conservation is violated by mixing, and explicitly by the mass splittings among the bosons. Columns 3 and 4 of Table 1.1 list ΔG and the combination of mixing angles, boson mass and boson coupling measured by the reaction, expressed as a mass. The measured rates depend on the inverse fourth power of this mass. Column five lists the limit on this mass obtained from each reaction. In the model, reactions that separately violate lepton flavor and quark flavor but conserve total generation number ($\Delta G = 0$) are not ‘Cabibbo suppressed’. The generation number may have significance in some models where mixing in the quark and lepton sectors are related; in any event it serves as a means of classifying related processes.

1.3 Muon Number Violation - a Brief History

Accelerator searches {Steinberger:1955} {Conversi:1961} {Sard:1961} {Conforto:1962} {Bartley:1964} {Bryman:1972} {Badertscher:1979} {Ahmad:1988} {Dohmen:1993} for the muon number violating processes $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- N \rightarrow e^- N$ began 45 years ago with the experiments of Lokanathan and Steinberger ($\mu^+ \rightarrow e^+ \gamma$) and Steinberger and Wolfe ($\mu^- N \rightarrow e^- N$). The $\mu^- N \rightarrow e^- N$ neutrinoless transitions were studied theoretically, in 1958, by Feinberg {Feinberg:1958} and the phenomenology was developed in 1959 by Feinberg and Weinberg {Weinberg:1959}, several years before the two neutrino experiment. Two observations in that 1959 paper are of special relevance here. First, the conversion of a muon to an electron in the field of the nucleus occurs coherently, implying a two body final state and a monochromatic electron with energy approximately equal to the muon mass. It is this distinctive signature that makes the process attractive experimentally. Second, because of the “chiral character” of the weak interactions of the leptons, it is easy to imagine processes in which the muon to electron transition occurs through chirality conserving processes (e.g., four fermion interactions) while $\mu^+ \rightarrow e^+ + \gamma$, which requires a chirality change, is forbidden.

The subject was re-examined within the framework of gauge theories in 1977 by Marciano and Sanda {Marciano:1977} who studied $\mu^+ \rightarrow e^+ \gamma$, $\mu^- N \rightarrow e^- N$ and $\mu^+ \rightarrow e^+ e^+ e^-$ in a variety of gauge models. They pointed out the potential for these processes as probes of extensions to the Standard Model and emphasized that muon to electron conversion was the more probable reaction in many of the models.

In 1994 Barbieri and Hall {Barbieri:1994} proposed these same lepton flavor violating transitions as a way to test super-unified theories. In supersymmetric extensions of the Standard Model, stringent theoretical constraints are imposed on the squark and slepton mass spectra; both are required to be nearly degenerate to avoid flavor changing neutral currents and lepton flavor violation {Dine:1993}. In their proposed super-unified theory, the slepton mass degeneracy is broken, leading to flavor and CP-violating transitions. The results of the specific calculation and those of Hisano et al. {Hisano:1997} in Figure 1.1 are model dependent, but the physical mechanisms that lead to L_e , L_μ , and L_τ non-conservation are generic to supersymmetric quark-lepton unification.

On the experimental side, an excellent starting point is provided by the knowledge and experience obtained from the two most recent experiments at TRIUMF and the PSI, and from the MELC proposal {Djilkibaev:1989} {Abadjev:1992} to the Moscow Meson Factory. In the MELC proposal, a large increase in muon flux is predicted with a solenoidal collection scheme at the front end, as was adopted by the muon collider proponents, and many of the backgrounds that accompany this large flux were studied.

A collaborative effort, with the participation of groups from the University of California Irvine, Houston University, the Institute for Nuclear Research Moscow, New York University, Purdue University, and the University of Pennsylvania, resulted in a proposal to the Brookhaven National Laboratory, MECO, for a $\mu^- N \rightarrow e^- N$ conversion experiment with a sensitivity of $R_{\mu e} < 10^{-16}$ {Bachman:1997}. The experiment received scientific approval in October of 1997 from the BNL Program Advisory Committee, who were enthusiastic in their support:

The search for coherent muon-electron conversion at 10^{-16} sensitivity is an extremely powerful probe of lepton flavor violation and physics beyond the Standard Model. Such an experiment has the potential to become a flagship effort for AGS-2000 and could make a major discovery.

Since that time we have been joined by groups from Boston University, Brookhaven National Laboratory, The College of William and Mary, and Berkeley.

1.4 Muon to Electron Conversion - an Overview

Sensitive searches have been made for the two lepton flavor violating processes $\mu^+ \rightarrow e^+ \gamma$ and $\mu^- N \rightarrow e^- N$. The reactions are complementary, both theoretically and experimentally. On the theoretical side, if the $\mu^- N \rightarrow e^- N$ conversion is not Coulombic, e.g., if it is mediated by a heavy Z or non-standard Higgs, or proceeds through an effective four-fermion interaction (box diagrams), it has clear advantages over the decay process. In the supersymmetric grand unified theory of Ref. {Barbieri:1995}, on the other hand, both processes occur predominantly through effective chirality changing couplings ($\sim \sigma_{\mu\nu} q^\nu \times [1, \gamma_5]$), and the branching ratio for $\mu^+ \rightarrow e^+ \gamma$ is approximately 200 times larger than $R_{\mu e}$ in aluminum. The two experiments are different: $\mu^+ \rightarrow e^+ \gamma$ is limited by accidental backgrounds from radiative muon decay in which the photon and electron can come from either the same or different muon decays in a necessarily intense muon beam. A significant advantage for $\mu^- N \rightarrow e^- N$ is the absence of accidental coincidences of this kind; there is only one mono-energetic electron in the final state. Furthermore, the energy distribution of the background electrons from $\mu^+ \rightarrow e^+ \nu \bar{\nu}$ is peaked at the energy of the electron in $\mu^+ \rightarrow e^+ \gamma$, while background from muon decay electrons at the conversion electron energy, approximately the muon rest mass energy, are strongly suppressed. The current best experimental limit for $\mu^+ \rightarrow e^+ \gamma$ comes from the MEGA experiment at Los Alamos; that collaboration reported {Brooks:1999} their final result, $B(\mu^+ \rightarrow e^+ \gamma) < 1.2 \times 10^{-11}$ at 90% confidence level, limited by background. There currently exists an approved experiment {Barkov:1999} at the PSI with the goal of reaching a sensitivity of 10^{-14} . Muon to electron conversion experiments have reached a sensitivity of 6×10^{-13} .

1.4.1 Kinematics and Backgrounds

The backgrounds in $\mu^- N \rightarrow e^- N$ result principally from four sources: muon decay in orbit (DIO), radiative muon capture (RMC), prompt processes where the detected putative conversion electron is nearly coincident in time with a beam particle arriving at the stopping target, and cosmic ray induced electrons. Muon to electron conversion, $\mu^- N \rightarrow e^- N$ occurs coherently in the field of the nucleus, the

electron recoiling against the nucleus with energy $\approx m_\mu c^2$, $E_0 \cong E_\mu - \frac{E_\mu^2}{2M_A}$, where E_μ is the muon

energy, mass plus binding energy, before capture, and M_A is the mass of the nucleus. An electron of this energy, detected in a time window delayed with respect to the muon stop, signals the conversion. While a free muon decaying at rest can produce an electron whose energy is at most $m_\mu c^2/2$, the decay of a bound muon can result in an electron with energy approaching that of a conversion electron. At the kinematic limit in bound decay, the two neutrinos carry away no momentum and the electron recoils against the nucleus, simulating the two-body final state of $\mu \rightarrow e$ conversion. The differential spectrum falls rapidly near the endpoint, proportional to $(E_0 - E_e)^5$. We are currently planning to use two different target materials: Aluminium and Titanium but we will only consider Al here for discussion purposes. Different materials have different LFV conversion rates and can thus distinguish between theoretical models {Kitano:2002}. However, the energy spectrum of the converted electron also depends on the material {Shanker:1982} due to binding energy, nuclear recoil, etc.. In aluminum, the fraction of all muon decays that produce electrons within 3 MeV of the endpoint is about 5×10^{-15} .

Radiative muon capture will sometimes produce photons with energy approaching that of the muon rest mass but falling short because of the difference in mass of the initial and final nuclear states and the nuclear recoil energy. For capture on aluminum, the maximum photon energy is 102.5 MeV. The photon can convert in the target to an asymmetric electron- positron pair, resulting in an electron within 3.5 MeV of the conversion energy.

The above are the dominant physics backgrounds if prompt processes can be rejected. Pions stopping in the target are the major source of prompt background, and can produce photons with energy up to 140 MeV. Electrons in the beam that scatter in the target are another such prompt background, as is the decay in flight of a muon in the region of the target in which the muons stop. In addition, a cosmic ray muon or a photon that enters the detector region and produces an electron of 105 MeV can fake a muon conversion if the electron trajectory appears to originate in the stopping target.

1.4.2 Previous $\mu^- N \rightarrow e^- N$ Experiments

There is a long history of muon to electron conversion experiments {Steinberger:1955} {Conversi:1961} {Sard:1961} {Conforto:1962} {Bartley:1964} {Bryman:1972} {Badertscher:1977} {Ahmad:1988} {Dohmen:1993} dating from the 1955 experiment of Steinberger and Wolfe. The techniques employed in the more recent experiments provide important input in our effort to reach the levels prescribed by supersymmetric grand unification. We focus on the last two, whose properties and results are listed in the first two columns of Table 1.2.

Table 1.2 The table gives the main features of the two most recent $\mu^- N \rightarrow e^- N$ searches in columns 2 and 3, and for the MECO experiment proposed for BNL in column 4.

Features	TRIUMF {Ahmad:1988}	SINDRUM2 {Dohmen:1993}	MECO {Bachman:1997}
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Principal detector	TPC, 0.9T	Drift Chamber, 1.2T	Straw tubes, 1.0T
Target material	Titanium	Titanium	Aluminum/Titanium
μ^- in/stopped [Hz]	$1.3/1.0 \times 10^6$	$12/3.3 \times 10^6$	$2.5/1 \times 10^{11}$
π/μ stops	10^{-4}	10^{-7}	10^{-11}
Prompt rejection	Beam counters	Beam counters	Pulsed beam
FWHM Resolution [MeV]	4.5	2.3	0.78
Exposure time	100 days	25 days	150 days
Cosmic ray background	$\sim 0.15/\text{MeV}$	Negligible	Negligible
90% CL Limit	4.6×10^{-12}	6.1×10^{-13}	5×10^{-17}

In the 1993 SINDRUM2 experiment, electrons with transverse momenta below 112 MeV/c were trapped in helical trajectories in the 1.2 T field of a super-conducting solenoid, 1.35 m in diameter and 1.8 m long. Those with sufficient momentum to reach cylindrical Cerenkov hodoscopes at the ends of the solenoid triggered the system and their momenta were measured in cylindrical tracking chambers. The beam, $1.2 \times 10^7 \mu^-/\text{s}$, was brought in along the axis of the solenoid; 28% stopped in a titanium target. The ratio of π^- to μ^- stops was 10^{-7} .

The 1988 TRIUMF experiment was similar; it used a hexagonal time projection chamber situated in a 0.9 T axial field. About $1.0 \times 10^6 \mu^-/\text{s}$ were stopped in a titanium target; the ratio of π^- to μ^- stops was 10^{-4} .

In both the 1988 TRIUMF experiment and the 1993 SINDRUM2 experiment, the beam intensity was low enough to use scintillation counters in the beam to veto events coincident with the arrival of a particle at the stopping target. Figure 1.2 shows graphically the events in the region 85-120 MeV in the SINDRUM2 experiment. The plot shows the data (i) before suppression of any backgrounds, (ii) after suppression of prompt backgrounds and (iii) after suppression of prompt and cosmic backgrounds. The remaining events are consistent with having come entirely from muon decay in orbit. The highest energy electron detected had an energy of 100.6 MeV. In the earlier TRIUMF experiment, there were no events in the window $96.5 \text{ MeV}/c \leq P_e \leq 106 \text{ MeV}/c$, where 85% of all $\mu-e$ conversion electrons were expected. Nine events with momenta $> 106 \text{ MeV}/c$ were observed; the source of most of these events was thought to be cosmic rays. This cosmic ray leakage through the shield was confirmed in a separate experiment in which the cosmic ray induced background was measured with the beam turned off. These two experiments achieved similar sensitivities, $R_{\mu e} < 4 \times 10^{-12}$. The limit from the SINDRUM2 experiment has since been lowered by a factor of six in a fifty day exposure (3×10^{13} stopped muons) to 6.1×10^{-13} . At ten times the intensity, beam counters can no longer be used to reject prompts. A high flux beam line and a pion to muon converter situated inside an 8.5 m long super-conducting solenoid has been commissioned. It is calculated that this could reduce prompt backgrounds to a negligible level.

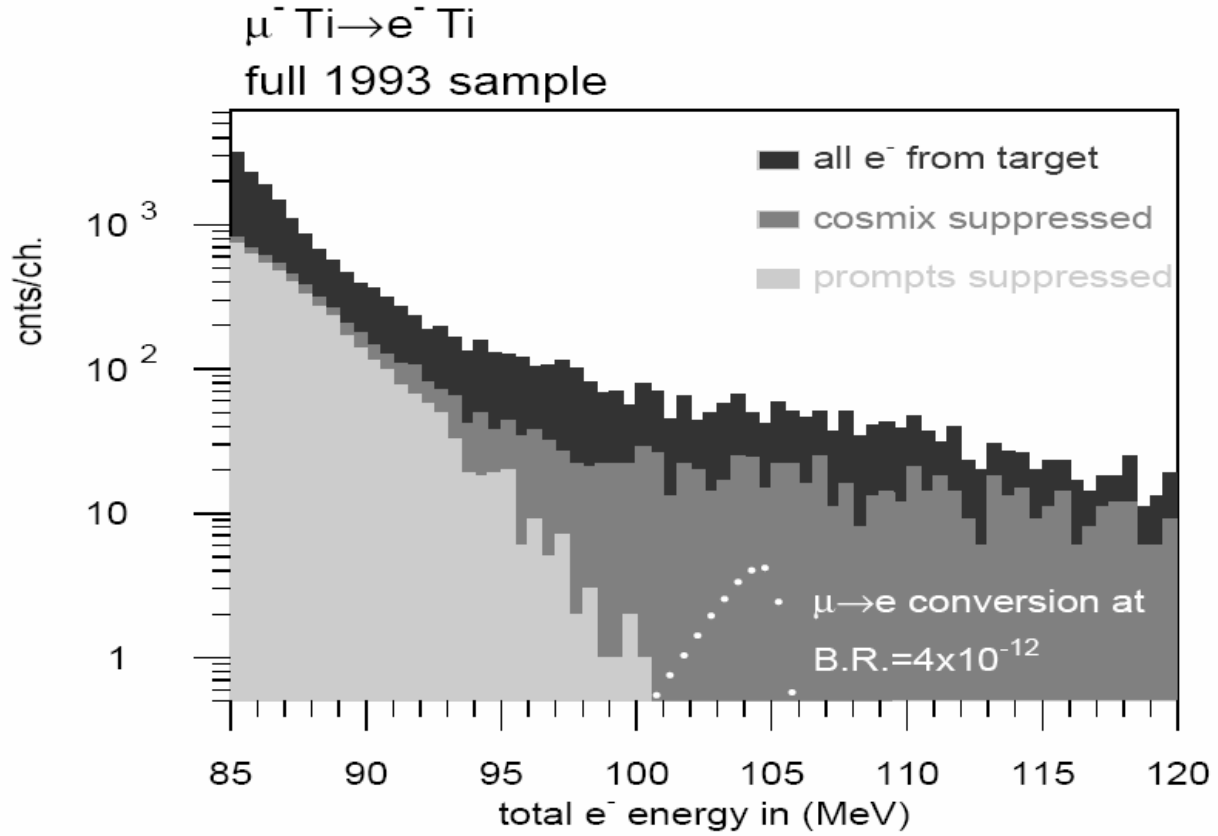


Figure 1.2 Electron energy spectrum from SINDRUM2 experiment. There is no background above 101 MeV after suppression of cosmics and prompts.

1.4.3 Choice of Muon Conversion Target

For coherent $\mu^- N \rightarrow e^- N$ conversion in the nuclear Coulomb field the ratio $R_{\mu e}$ was found in reference {Weinberg:1959} to increase with Z , as $Z|F_p|^2$, where F_p is the form factor that describes the nuclear charge distribution, as measured for example in low energy $e-N$ scattering. Relativistic calculations have been done by Shanker {Shanker:1979} and, more recently, by Czarnecki, Marciano, and Melnikov {Czarnecki:1998}, that take into account the Coulomb distortion of the outgoing electron's wave function in addition to the effect of the finite nuclear size. While these results do not differ dramatically from the earlier one, they do decrease the conversion rate at high Z , where the effects considered are expected to have an impact. The result is that $R_{\mu e}$ increases with Z between aluminum ($Z = 13$) and titanium ($Z = 22$) but saturates and then falls, the value of $R_{\mu e}$ for lead ($Z = 82$) is only 15% higher than for aluminum.

The factor of 1.7 improvement in going from aluminum to titanium needs to be compared by the difficulty in dealing with prompt backgrounds that result from the much shorter muon lifetime in titanium. The longer lifetime in aluminum ($\tau = 0.88 \mu\text{s}$) permits using a pulsed proton beam to produce muons, delaying the detection time window for the conversion electron by 600-700 ns, well beyond the arrival time at the stopping target of nearly all particles, without a significant loss in sensitivity. An added advantage is that very pure targets of aluminum are available and the endpoint is close to the muon mass. A muon decaying in orbit around a low Z impurity in a high Z target, on the other hand, can produce an electron with energy beyond the nominal endpoint. We are currently considering to running

the experiment with both materials in consecutive running periods since there are advantages and disadvantages with either one. Furthermore, different materials have different LFV conversion rates and in the event of a positive signal, they can be used to distinguish between theoretical models {Kitano:2002}.